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Technical Area-Lightning and High Energy Radiation

Title: Lightning Initiation and Propagation
from

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TABLE OF CONTENTS

	Page
Executive Summary	3
I. Introduction and Overview of Results.....	4
II. Detailed Results.....	8
III. Background for the Reported Research	11
IV. Proposed Future Research	14
V. References.....	16

Lightning Initiation and Propagation

Executive Summary

The University of Florida (UF) and Florida Institute of Technology (FIT) have completed a one-year, exploratory (seedling) program (March 25, 2008 to August 22, 2009, DARPA Grant HR001-08-1-088) that has examined various aspects of lightning initiation and propagation including the role of X-rays, gamma rays, and cosmic rays in the initiation and propagation of lightning and in the phenomenology of thunderclouds. The experimental portion of the research has taken place at the International Center for Lightning Research and Testing (ICLRT) in north-central Florida. The deliverables of the exploratory grant include the material described in the following journal papers. This material additionally serves to demonstrate the UF-FIT experimental and theoretical capabilities in the subject area:

1. Saleh et al. (2009), Properties of the x-ray emission from rocket-triggered lightning as measured by the Thunderstorm Energetic Radiation Array (TERA), J. Geophys. Res, Vol. 114, accepted for publication, Z. Saleh, J. Dwyer, J. Howard, M. Uman, M. Bakhtiari, D. Concha, M. Stapleton, D. Hill, C. Biagi and H. K. Rassoul
2. Dwyer et al. (2009), Remote measurements of thundercloud electrostatic fields, J. Geophys. Res., 114, D09208, doi:10.1029/2008JD011386, J. R. Dwyer, M. A. Uman, and H. K. Rassoul
3. Dwyer et al. (2009), Estimation of the fluence of high-energy electron bursts produced by thunderclouds and the resulting radiation doses received in aircraft, J. Geophys. Res., Vol. 114, accepted for publication
4. Biagi et al. (2009), High-speed Video Observations of Rocket-and-Wire Initiated Lightning, Geophys. Res. Lett., Vol.36, L15801, doi:10.1029/2009GL038525, 2009, C. J. Biagi, D. M. Jordan, M. A. Uman, J. D. Hill, W. H. Beasley, and J. Howard
5. Howard et al. (2009), RF and x-ray source locations during the lightning attachment process, J. Geophys. Res., submitted and under review.
6. Nag et al. (2009) On phenomenology of compact intracloud lightning discharges, J. Geophys. Res., submitted and under review.
7. Nag and Rakov (2009), Some inferences on the role of positive charge region in facilitating different types of lightning, Geophys. Res. Lett., 36,L05815,2009,doi:10.1029/2008GL036783
8. Nag and Rakov (2009), Electromagnetic pulses produced by bouncing-wave-type lightning discharges, IEEE Trans. on EMC, Vol. 51, No. 3,

pp. 466-470, August 2009, A. Nag and V. A. Rakov

Lightning Initiation and Propagation

I. Introduction and Overview of Results

In the one-year exploratory DARPA program that began March 25, 2008, we have investigated a variety of issues related to lightning initiation and propagation, with special attention to the role of x-rays and other high energy radiation in these two processes. The deliverables from that exploratory program are, in part, contained in the papers written to describe the salient results of the research. Those paper titles and Abstracts are listed below.

1. Properties of the x-ray emission from rocket-triggered lightning as measured by the Thunderstorm Energetic Radiation Array (TERA), J. Geophys. Res. Vol. 114 accepted for publication, Z. Saleh, J. Dwyer, J. Howard, M. Uman, M. Bakhtiari, D. Concha, M. Stapleton, D. Hill, C. Biagi, and H. Rassoul

Abstract

The Thunderstorm Energetic Radiation Array (TERA) is located at the University of Florida/Florida Tech International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL. The array includes 45, 7.6-cm diameter NaI/photomultiplier tube detectors enclosed in 24 separate aluminum boxes that shield the detectors from light, moisture and RF noise. The array covers the ~ 1 km² ICLRT facility, centered on the rocket launch tower, used to trigger lightning. From 2005 to 2007, TERA recorded 7 rocket-triggered lightning flashes. In this paper, we present an analysis of the x-ray emission of three of these flashes. The x-ray emission is observed to occur during the dart leader phase of each stroke, just prior to the time of the return stroke. Significant x-rays are observed on all the detectors out to a distance of 500 m from the lightning channel for times up to 200 microseconds prior to the start of the return stroke. Using Monte Carlo simulations to model the x-ray propagation, we find that the energetic electrons that emit the x-rays have a characteristic energy of about 2 MeV for these particular events. The x-ray emission, which is the most intense near the channel and decreases exponentially with a 60 m length scale, is most consistent with the energetic source electrons emitted isotropically from the dart leader. It is also found that the x-ray and energetic electron luminosities of the dart leader channel decreases with height above the ground. These results help shed light onto the mechanism for producing energetic radiation from lightning.

2. Remote measurements of thundercloud electrostatic fields, J. Geophys. Res., 114, D09208, doi:10.1029/2008JD011386, J. R. Dwyer, M. A. Uman, and H. K. Rassoul

Abstract

Analytical and numerical models of the radio-frequency emissions produced by relativistic runaway electron avalanches initiated by cosmic-ray extensive air

showers are presented. It is found that single point measurements of the distant electromagnetic fields allow the remote determination of the electrostatic field in the runaway electron avalanche region. For instance, it is possible to use ground based and/or remote airborne measurements of the radio-frequency pulses from the runaway electron avalanches to map the magnitudes and directions of the electrostatic field within a thundercloud for regions with electric fields above the runaway avalanche threshold. Such measurements, which are difficult to perform *in situ*, may help answer several key questions regarding lightning initiation, such as what electric fields are usually present when lightning initiates and whether electric fields in small regions ever reach the conventional breakdown field.

3. Estimation of the fluence of high-energy electron bursts produced by thunderclouds and the resulting radiation doses received in aircraft, J. Geophys. Res. Vol. 114 accepted for publication, J. R. Dwyer, D. M. Smith, M. A. Uman, Z. Saleh, B. Grefenstette, B. Hazelton, and H. K. Rassoul,

Abstract

Using recent x-ray and gamma-ray observations of terrestrial gamma-ray flashes (TGF) from spacecraft and of natural and rocket-triggered lightning from the ground, along with detailed models of energetic particle transport, we calculate the fluence of high-energy (MeV) electrons, x-rays and gamma-rays likely to be produced inside or near thunderclouds in high electric field regions. We find that the x-ray/gamma-ray fluence predicted for lightning leaders propagating inside thunderclouds agrees well with the fluence calculated for TGFs, suggesting a possible link between these two phenomena. Furthermore, based upon reasonable assumptions about the magnitude and extent of the electric fields, we estimate that the fluence of high-energy runaway electrons can reach dangerous levels at aircraft altitudes. If an aircraft happened to be in or near the high-field region when either lightning is present or a TGF-like event is occurring, then the radiation dose received by passengers and crew members inside that aircraft could potentially approach 0.1 Sv in less than 1 millisecond. Considering that commercial aircraft are struck by lightning, on average, one to two times per year, the risk of such large radiation doses should be investigated further.

4. High-speed Video Observations of Rocket-and-Wire Initiated Lightning, Geophys. Res. Let., Vol.36, L15801, doi:10.1029/2009GL038525, 2009, C. J. Biagi, D. M. Jordan, M. A. Uman, J. D. Hill, W. H. Beasley, and J. Howard

Abstract

We present observations of a rocket-and-wire triggered lightning flash obtained with high-speed video cameras (frame times 185 μ s and 20 μ s) with time-synchronized current and electric field measurements. Transient leader channels were observed time-correlated with precursor current pulses occurring prior to the development of the sustained upward positive leader that initiated the initial continuous current. The sustained upward positive leader stepped with a constant speed of 5.6×10^4 m s⁻¹ over its initial 100 m. The wire destruction occurred

discontinuously over a time of about 7 ms about 45 ms after sustained upward leader inception, with a small change in channel current. Downward leaders, upward connecting leaders, streamer zones and filamentary streamers were imaged in the bottom 50 m of the channel. We present the first images of the formation of a negative step in lightning apparently involving a space stem similar to steps in meter-length negative laboratory sparks.

5. RF and X-ray source locations during the lightning attachment process, J. Geophys. Res., under review, J. Howard, M.A. Uman, C. Biagi, D. Hill, J. Jerauld, V. A. Rakov, J. Dwyer, Z. Saleh, and H. Rassoul

Abstract

Using an eight-station array of electric field derivative (dE/dt) sensors and co-located NaI X-ray detectors, we have obtained three-dimensional RF source locations during the leaders and attachment processes of three natural first cloud-to-ground strokes initiated by stepped leaders and one stroke initiated by a dart-stepped leader in a rocket-and-wire triggered flash. Stepped leader and dart-stepped leader dE/dt pulses are tracked from a few hundred meters to a few tens of meters above ground, after which pulses of different characteristics than the step pulses are observed to occur at lower altitudes. These post-leader pulses include (1) the "leader burst", a group of pulses in the dE/dt waveform radiated within about 1 μ s and occurring just prior to the slow front in the corresponding return stroke electric field waveform; (2) dE/dt pulses occurring during the slow front; and (3) the fast transition or dominant dE/dt pulse that is usually associated with the rapid transition to peak in the return stroke electric field waveform. Additionally, the timing coincidence between X-rays and dE/dt pulses on co-located measurements is used to examine the X-ray production of the post-leader processes. Leader bursts are the largest X-ray producers of the three post-leader processes and exhibit propagation speeds that exceed the preceding stepped leader speeds by more than an order of magnitude. Slow-front and fast-transition pulses appear to originate from similar physical processes, probably the multiple connections of upward and downward leaders. However, more X-rays are coincident with slow-front pulses than with fast-transition pulses.

6. On phenomenology of compact intracloud lightning discharges, J. Geophys. Res., under review, Amitabh Nag, Vladimir A. Rakov, Dimitris Tsalikis and John A. Cramer

Abstract

We examined wideband electric fields, electric and magnetic field derivatives, and narrowband VHF (36 MHz) radiation bursts produced by 157 Compact Intracloud Discharges (CIDs). These poorly understood lightning events appear to be the strongest natural producers of HF-VHF radiation. All the events transported negative charge upward (or lowered positive charge), 150 were located by the NLDN and 149 of them were correctly identified as cloud discharges. NLDN-reported distances from the measurement station were 5 to 132

km. Three types of wideband electric field waveforms, were observed. About 72% of CIDs occurred in isolation, 24% occurred prior to, during, or following cloud-to-ground lightning, and 4% occurred in pairs, separated by less than 200 ms ("multiple" CIDs). For a subset of 48 CIDs, the geometric mean of radiation source height was estimated to be 16 km. It appears that some CIDs actually occurred above cloud tops in clear air or in convective surges (plumes) overshooting the tropopause and penetrating deep into the stratosphere. For the same 48 CIDs, the geometric mean electric field peak normalized to 100 km (inclined distance) was as high as 20 V/m and for 22 events within 10-30 km (horizontal distance) it was 15 V/m, both of which are higher than that for first strokes in negative cloud-to-ground lightning. The geometric means of total pulse duration, width of initial half-cycle, and ratio of initial electric field peak to opposite polarity overshoot were 23 μ s, 5.6 μ s, and 5.7, respectively.

7. Some inferences on the role of positive charge region in facilitating different types of lightning, *Geophys. Res. Lett.*, 36, L05815, 2009, doi:10.1029/2008GL036783, Amitabh Nag and Vladimir A. Rakov

Abstract

It is generally thought that the lower positive charge region (LPCR) serves to enhance the electric field at the bottom of the main negative charge region and thereby facilitate the launching of a negatively-charged leader toward ground. On the other hand, the presence of excessive lower positive charge region may prevent the occurrence of negative cloud-to-ground discharges by "blocking" the progression of descending negative leader from reaching ground and thus "converting" the potential cloud-to-ground flash to an intracloud (or cloud-to-air) one. We examined variations in occurrence of preliminary breakdown (PB) pulse trains in CG flashes. Assuming that the PB pulse train is a manifestation of interaction of a downward extending negative leader channel with the LPCR, we qualitatively examined the inferred dependence of lightning type on the magnitude of this charge region. The result is a set of conceptual scenarios that can be tested by future observations.

8. Electromagnetic Pulses Produced by Bouncing-Wave-Type Lightning Discharges, *IEEE Trans. on EMC, Special Issue on Lightning*, Vol. 51, No. 3, pp. 466-470, August 2009, A. Nag and V.A. Rakov

Abstract

Based on experimental evidence of multiple reflections and modeling, we infer that the so-called compact intracloud lightning discharge (CID) is essentially a bouncing-wave phenomenon. Some tens of reflections may occur at both radiating channel ends. The reflections have little influence on the overall CID electric field signature (narrow bipolar pulse (NBP) waveform), but are responsible for its fine structure, "noisiness" of dE/dt waveforms, and accompanying HF-VHF radiation bursts.

II. Detailed Results

We have studied the initiation and propagation of lightning, both the type that has its origin within the thundercloud and the type that originates near-ground level as a result of the presence or motion of overhead cloud charge, with a long-term goal of being able to specify definite criteria for initiation and propagation. We have modified the existing array of high energy particle and radiation detectors and the network of electromagnetic field measuring antennas at the ICLRT and in Gainesville so as to be able (1) to detect and record pertinent electric and magnetic field changes emanating from both overhead thunderclouds and near-ground while simultaneously detecting (2) the magnitude and direction-of-arrival and source altitude of X-rays and gamma rays emanating from thunderclouds and from lightning, and (3) the shower size (energy) and direction-of-arrival of extensive cosmic ray air showers (that have been hypothesized to play a part in lightning initiation) via the secondary particles (mostly electron/positrons and muons) they produce. We have used high-speed video cameras capable of taking tens to hundreds of thousands of frames per second (up to 3 μ s frame durations). The optical system has been used to study the triggering of lightning by the rocket and wire technique and is complimented by the measurement of the ambient initiating electric field at ground level at two or more locations, as part of a system to measure the initiating field above the Earth as a function of altitude. We have specifically studied "compact intracloud discharges" as part of potential in-cloud lightning initiation processes. The data recorded from the overall new system of high-energy radiation, electromagnetic fields, and optical imaging measurements will allow advances in our understanding of the relationship between (1) lightning initiation and propagation, both cloud-originated and ground-originated and (2) x-rays, gamma rays, and cosmic rays. More details follow:

- (1) We have expanded upon the high-speed photographic work described in Biagi et al. (2009) (Ref. 4 above) on triggered lightning by recording lightning processes at higher speeds than the previous 20 μ s/frame (up to 3 μ s/frame) and measuring upward-leader currents at less than one-ampere sensitivity, lower than was previously possible. An annotated list of rocket-and-wire triggered events to this writing is given in Table 1 including those after the grant closing date that were acquired as part of a continuation of the grant. Analysis of these data is part of the PhD work of Chris Biagi.
- (2) We have expanded the x-ray and dE/dt measurements and hence the resulting source locations of Howard et al. (2009) (Ref. 5 above) by developing and employing a ten-station time-of-arrival source-location x-ray network using new large plastic scintillation sensors, allowing a more advanced study of leader propagation and of the attachment process to ground. Howard et al. (2009) were able to follow the dE/dt and x-ray sources for 4 lightning flashes, three natural and one triggered, from about 500 m altitude to ground level, identifying new processes associated with the attachment process. We have extended this work to additional flashes using a larger network with more sensitive and faster time-resolution x-ray detectors, allowing better identification and location of events during leader propagation and attachment to ground. To date, one natural

lightning has been recorded on-site and one just off the site and numerous triggered events have been recorded as indicated in Tables 1 and 2. This work is part of the PhD dissertation of Jonathan D. Hill.

- (3) We have developed instrumentation to measure the static electric field in the thundercloud from the EM rf pulses observed on ground induced by cosmic-ray-caused runaway electron breakdown in the cloud, as described in Dwyer et al. (2009) (Ref. 2 above). Dwyer et al. (2009) has provided the theoretical groundwork for a new method of remotely measuring the electrostatic fields inside thunderclouds. This technique involves simultaneously measuring at ground level the cosmic-ray air showers and the 1mV/m- level rf pulses with submicrosecond risetimes radiated by the runaway breakdown current in the cloud. As part of the DARPA seedling, the air shower array measurement system and the EM-pulse-measuring system have been constructed and are presently being tested to search for an association of air showers and EM pulses.

Table 1. ICLRT Rocket Triggered Lightning Event List : June 24, 2008 - Present

Shot	Date	Time (UT)	Result	Strokes	Current (kA)	Fields (kV/m)	Gainesville	Interferometer	Comments
UF 08-04	6/29/08	21:36:29	IS	-	-	-5.2	-	-	Partial IS process; no return strokes
UF 08-05	6/29/08	N/A	Wire Break	-	-	-5.2	-	-	Wire broke at the launch tube (Tube 7); no trigger
UF 08-06	6/29/08	21:46:52	Wire Break	-	-	-5.6	-	-	Attempted shot of a stripped down altitude spool; wire came off in wads and broke; no trigger
UF 08-07	6/30/08	18:37:24	No Trigger	-	-	-5.4	-	-	Clean shot, no trigger
UF 08-08	6/30/08	18:41:24	IS & RS	5	18	-5.7	Y	-	Five stroke flash; first high speed Photron video; E/B field, dE/dt, X-ray, and Incident Current data acquired
UF 08-09	7/12/08	17:42:57	Wire Break	-	-	-5.6	-	-	Immediate wire cut on top of launch tube; no trigger
UF 08-10	7/12/08	17:44:27	Wire Break	-	-	-6.5	-	-	Triggering wire disconnected from the launcher and broke, no trigger
UF 08-11	7/12/08	17:52:49	IS & RS	3	17	-5.9	Y	-	Three stroke flash; Photron video, E/B field, X-ray, and Current data acquired
UF 08-12	7/23/08	18:40:21	IS	-	-	-5.8	-	-	Partial IS process; no Photron video
UF 08-13	7/27/08	20:22:21	IS	-	-	-6.2	-	-	Partial IS process; no Photron video
UF 08-14	7/28/08	18:45:33	Wire Break	-	-	-5.0	-	-	Wire broke 50m out of launch tube; no trigger
UF 08-15	9/10/08	21:43:50	No Trigger	-	-	-5.4	-	-	First fence wire shot; first good high-sensitivity current record (up to ~100A) of precursor current pulses; no trigger
UF 08-16	9/11/08	20:30:55	No Trigger	-	-	-5.6	-	-	Clean shot, but no trigger; May have had been a nearby lightning discharge just prior to launch
UF 08-17	9/11/08	20:36:56	IS	-	-	-5.3	-	-	Full IS process (wireburn); Current jumped to return stroke path to ground
UF 08-18	9/17/08	22:04:15	IS & RS	9	21	-6.3	N	-	Nine stroke flash; Excellent Photron videos showing upward/downward leaders in same frame; Partial dataset of E/B field, X-ray, & Current
UF 08-19	10/9/08	18:11:39	IS & RS	3	18.2	-5.4	Y	-	Three stroke flash; E/B field, X-ray, and Current data acquired. No Photron video.
UF 08-20	10/9/08	18:24:15	IS & RS	5	11.7	-5.3	Y	-	Five stroke flash; Photron video, E/B field, X-ray, and Current data acquired.

Shot	Date	Time (UT)	Result	Strokes	Current (kA)	Fields (kV/m)	Gainesville	Interferometer	Comments
UF 08-21	10/9/08	19:17:48	IS & RS	2	17.2	-5.2	N	-	Two stroke flash; Photron Video and partial dataset of E/B field and Current data acquired
UF 09-01	2/19/09	12:40:53	IS	0	-	4.5	-	-	First shot in positive fields (old spool). Large spark witnessed at both top and bottom of tower.
UF 09-02	2/19/09	12:55:28	Wire Break	-	-	-4.0	-	-	Immediate wire break and no static field change (old spool)
UF 09-03	2/19/09	13:00:21	No Trigger	-	-	4.0	-	-	Positive fields shot (new spool). Wire unspooled properly but no IS processes recorded.
UF 09-04	2/19/09	13:04:05	IS	0	-	-4.6	-	-	Full IS process (wireburn) with no subsequent return strokes (old spool)
UF 09-05	2/19/09	13:13:43	Wire Break	-	-	4.1	-	-	Positive fields shot with fence wire spool. Wire broke shortly after rocket exited the tube resulting in a very small static field change.
UF 09-06	3/28/09	01:56:06	IS & RS	5	17.3	-6.0	Y	-	First successful trigger of 2009; 8 seconds between launch and IS process; bipolar fourth stroke; discontinuity at base of wire; Phantom video and full dataset of E/B field, X-ray, and Current data
UF 09-07	3/28/09	02:15:03	No Trigger	-	-	-5.4	-	-	Clean shot, wire unspooled properly, no trigger
UF 09-08	3/28/09	02:36:29	Wire Break	-	-	-5.3	-	-	Immediate wire break, no trigger
UF 09-09	4/14/09	13:52:39	No Trigger	-	-	5.5	-	-	Positive fields shot. Very high winds; rocket may not have reached altitude
UF 09-10	5/26/09	20:11:09	No Trigger	-	-	-5.2	-	-	Nearby lightning produced a field break immediately after rocket launch; no trigger
UF 09-11	5/26/09	20:13:25	IS & RS	1	N/A	-5.7	N	-	One stroke flash; no MSE trigger due to malfunctioning high-current measurement; Photron/Phantom video and partial dataset of E/B field and Current waveforms
UF 09-12	5/26/09	20:31:21	IS & RS	1	36.3	-5.1	N	-	One stroke flash, excellent Photron/Phantom video and full data set of E/B field, X-ray, and Current waveforms
UF 09-13	5/27/09	20:19:37	Alt.Trigger	8	N/A	-6.0	Y	-	Wire break and subsequent eight stroke altitude trigger to the catenary wires over Launch Control; Excellent Photron/Phantom video and full data set of E/B field, X-ray, and Current waveforms
UF 09-14	6/4/09	20:10:43	No Trigger	-	-	-5.1	-	-	Clean shot, wire unspooled properly, no trigger
UF 09-15	6/4/09	20:20:20	IS	-	-	-6.7	-	-	Full IS process (wireburn), Photron/Phantom video and partial dataset of E/B field and Current waveforms
UF 09-16	6/4/09	20:22:36	No Trigger	-	-	-6.5	-	-	Very good fields; Clean shot, wire unspooled properly, no trigger

Shot	Date	Time (UT)	Result	Strokes	Current (kA)	Fields (kV/m)	Gainesville	Interferometer	Comments
UF 09-17	6/4/09	20:37:26	IS & RS	4	46.3	-6.0	Y	-	Four stroke flash with peak current of over 46 kA (very strong), Excellent Photron/Phantom video, still photographs, and full dataset of E/B field, X-ray, and Current waveforms
UF 09-18	6/6/09	20:01:13	No Trigger	-	-	-5.7	-	-	Clean shot, great conditions, no trigger
UF 09-19	6/6/09	20:17:32	No Trigger	-	-	-6.6	-	-	Clean shot, great conditions, no trigger
UF 09-20	6/18/09	16:33:46	IS & RS	4	20.1	-7.4	N	-	Four stroke flash. Excellent Photron/Phantom video, still photographs, and full dataset of E/B field, X-ray, and Current waveforms; Few X-rays produced
UF 09-21	6/18/09	16:44:42	IS	-	-	-3.7	-	-	Full IS process (wireburn). Field break immediately before shot coincident with offsite lightning; Phantom video and partial dataset of E/B field and Current waveforms acquired
UF 09-22	6/18/09	16:57:48	IS & RS	7	15.5	-5.6	Y	-	Seven stroke flash; relatively weak peak current; Excellent Photron/Phantom video and full dataset of E/B field, X-ray, and Current waveforms; Few X-rays produced.
UF 09-23	6/18/09	17:23:19	No Trigger	-	-	5.0	-	-	Positive fields shot; Clean shot, wire unspooled properly, no trigger
UF 09-24	6/29/09	21:06:59	No Trigger	-	-	-5.3	-	-	Clean shot, no trigger, many pre-cursor pulses recorded on sensitive E-field and sensitive Current measurements; Phantom video
UF 09-25	6/29/09	21:09:13	IS & RS	5	32.9	-5.9	Y	-	Five stroke flash with fifth-stroke dart-step leader; Photron/Phantom video and full dataset of E/B field, X-ray, and Current waveforms; amazing still photograph captured with loop in fifth stroke channel
UF 09-26	6/29/09	21:18:32	IS & RS	5	28.8	-5.4	N	-	Five stroke flash with fourth stroke dart-step leader, Photron/Phantom video and full dataset of E/B field, X-ray, and Current waveforms
UF 09-27	6/29/09	21:31:19	IS & RS	7	29.2	-4.9	N	-	Six stroke flash, Photron/Phantom video and full dataset of E/B field, X-ray, and Current waveforms
UF 09-28	6/30/09	12:58:35	No Trigger	-	-	-6.5	-	Y	Lots of pre-cursor pulses; wire did not unspool cleanly; nearby cloud discharge
UF 09-29	6/30/09	13:49:13	IS & RS	5	19.5	-8.5	Y	Y	Five stroke flash in extremely high fields at ground; Photron/Phantom video and full dataset of E/B field, X-ray, and Current waveforms
UF 09-30	6/30/09	14:01:00	IS & RS	1	30.8	-7.2	Y	Y	Strong one stroke flash; 18.4 kA bipolar ICC pulse, possible dart-step leader; Photron/Phantom video and full dataset of E/B field, X-ray, and Current waveforms
UF 09-31	6/30/09	14:12:20	IS & RS	5	14.6	-8.1	N	-	Five stroke flash with small current amplitude, Photron/Phantom video and full dataset of E/B field, X-ray, and Current waveforms

Shot	Date	Time (UT)	Result	Strokes	Current (kA)	Fields (kV/m)	Gainesville	Interferometer	Comments
UF 09-32	7/7/09	15:12:54	IS & RS	1	20.4	-6.5	N	-	One stroke flash; no nearby lightning for hour but high fields; return stroke was and "altitude" type trigger, Photron/Phantom video and full dataset of E/B field, X-ray, and Current waveforms
UF 09-33	7/7/09	19:06:07	No Trigger	-	-	-6.0	-	-	Good fields, lots of precursor pulses recorded on sensitive E-field and Current measurements, rocket may have veered west; Phantom video
UF 09-34	7/9/09	17:15:34	IS & RS	3	17.7	-5.6	Y	-	Three stroke flash; Photron video in OT & LC; full dataset of E/B field, X-ray, and Current waveforms but minimal x-ray emission
UF 09-35	7/14/09	21:07:57	IS	-	-	-6.4	-	Y	Full IS process (wireburn), Phantom video and partial dataset of E/B field, X-ray, and Current waveforms
UF 09-36	7/14/09	21:19:06	No Trigger	-	-	-7.0	-	Y	Great fields, clean shot, but no trigger
UF 09-37	7/14/09	21:21:21	IS	-	-	-6.6	-	Y	Full IS process (wireburn), Phantom video and partial dataset of E/B field, X-ray, and Current waveforms
UF 09-38	7/14/09	21:25:15	IS & RS	1	29.8	-6.7	Y	Y	One stroke flash; no x-ray emission; Photron video in OT/LC; full dataset of E/B field, X-ray, and Current waveforms
UF 09-39	7/17/09	17:10:49	No Trigger	-	-	-5.1	-	-	Rocket veered sharply to the south; lots of precursor pulses; no trigger
UF 09-40	7/18/09	15:25:01	IS	-	-	-5.2	-	Y	Full IS process (wireburn); Phantom video in OT; lots of precursor pulses recorded on sensitive E-field and Current measurements
UF 09-41	08/18/09	16:22:25	IS	-	-	-6.4	-	Y	Full IS process (wireburn). No high-speed video or field records saved.
UF 09-42	08/18/09	16:24:39	IS & RS	-	16	-7.4	Y	Y	Possible large ICC pulse or single stroke flash, full dataset of E/B field, X-ray, and Current waveforms; Photron/Phantom video, high-speed spectrometer, RADAR
UF 09-43	08/18/09	16:30:09	IS & RS	-	25.3	-7.3	Y	Y	Five stroke flash; fast field records & x-rays acquired; Photron video in Launch Control; spectrometer and RADAR

Table 2. ICLRT Natural Lightning Event List: June 24, 2008 - Present

Event	Date	GPS Time (UT)	Strokes	NLDN Peak Current (kA)	Comments
MSE 08-01	7-5-08	00:04:52.438689	2	30	Onsite negative flash terminating on ground in SW corner of network; very minimal X ray production
MSE 08-02	7-6-08	04:09:40.363680	8	132	Offsite negative flash, no ground termination in network boundaries; network triggered optically on one stroke, possibly due to an overhead horizontal branch
MSE 09-01	06-03-09	20:10:18.552592	5	N/A	Offsite negative flash terminating to the SW of IS4. E-field records indicate 5-stroke multiplicity. Weak dE/dt and few x-ray recorded.
MSE 09-02	06-30-09	11:21	1	N/A	Onsite negative flash terminating south of NEO and east of ST4. Significant x-ray emission recorded on seven plastic detectors and all NaI detectors. Full dataset of dE/dt, E-field, and B-field. No video.

- (4) We have further investigated electric breakdown processes in the cloud (preliminary breakdown pulse trains and "compact intracloud discharges") in the manner described in Nag and Rakov (2009) (Ref. 7 above) and Nag et al. (2009) (Ref. 6 above), including new coincident x-ray and gamma ray measurements. Some details follow. According to Gurevich et al. (2003), the formation of a field-enhancing conductor ("lightning seed") in the cloud by a cosmic-ray particle with energy of 10^{16} eV via the runaway breakdown mechanism is associated with a current pulse having an amplitude of 100-200 A. This current pulse is predicted to generate a bipolar electric field pulse with a characteristic full width of 0.2 – 0.4 μ s (Gurevich et al., 2002). Gurevich et al. (2003) presented submicrosecond-full-width electric field pulses measured 5 – 20 km from lightning discharges that they interpreted as indicative of strong current pulses associated with the formation of the "lightning seed". Our preliminary measurements show that about 25% of the pulses in cloud and cloud-to-ground discharges have total durations less than 1 μ s (Nag et al. 2009b). However, it is not clear how the occurrence of multiple submicrosecond-scale pulses can be related to the runaway breakdown lightning initiation mechanism proposed by Gurevich et al. Further, Gurevich and Zybin (2005) hypothesized that the process giving rise to narrow bipolar pulses (NBPs), electromagnetic signatures of "compact intracloud discharges", also involves the runaway breakdown and that these pulses are wider than the hypothesized CG-initiating pulses because NBPs occur at higher altitudes. Comparison of model-predicted electric field pulses with measurements appears to be one of the most promising approaches to testing the validity of runaway breakdown models. We continue our search for pulses predicted by Gurevich et al.

We have examined the initial breakdown in both CG and IC flashes by measuring its electric field, dE/dt , dB/dt , VHF, and x-ray signatures. Special attention is being paid to recently documented preliminary breakdown pulse trains not followed by return-stroke waveforms (Nag and Rakov 2008) and to NBPs. Among other things, we are going to check, using an x-ray detector (provided by Dr. J. Dwyer of FIT) in Gainesville, if preliminary breakdown and NBP processes produce energetic radiation, like the gamma-radiation burst originated from some in-cloud process associated with a rocket-triggered flash at Camp Blanding (Dwyer et al. 2004). It is presently unknown if there exist NBPs that are not accompanied by HF-VHF radiation. On the other hand, it appears that there are VHF bursts which are characteristic of NBPs, but are not accompanied by characteristic wideband electric field signatures (e.g., Jacobson, 2003). We have a number of examples of such events and plan to examine them in detail. This has important implications for recent claims (H.-D. Betz, personal communication, 2008) that VLF/LF lightning locating networks can compete with VHF systems in reporting "total lightning". Further, the proportion of positive and negative NBPs is not yet reliably established. Smith et al. (2002) found that 29% of the ~13,000 narrow bipolar pulses recorded by the Los Alamos Sferic Array (consisted of five stations in New Mexico in 1998 and expanded to 11 stations in New Mexico, Texas, Florida, and Nebraska in 1999) had positive (atmospheric electricity sign convention) initial half-cycles. From the data acquired by the same Sferic Array

(LASA), Suszcynsky and Heavner (2003) reported that 37% of the narrow bipolar pulses had positive (atmospheric electricity sign convention) initial half-cycles in 2001 and 2002, and Smith et al. (2004) found 42% for a larger sample of over 100,000 events recorded during the period from 1998 to 2001. We will try to reduce the uncertainty in the proportion of positive and negative NBPs

- (5) We have begun the development of more sophisticated modeling of Terrestrial Gamma Ray Flash (TGF) doses to individuals in aircraft using detailed Monte Carlo simulations, building upon work by Dwyer et al. (2009) (Ref. 3 above). Progress has been made modeling TGFs using the relativistic feedback model of runaway breakdown. This model can now account for the correct fluence of runaway electrons and the accompanying gamma-rays; it predicts the correct pulse structure and naturally explains the multiple pulses observed by CGRO/BATSE.

III. Background for the Reported Research

For completeness, we now review some background information pertinent to the reported research. The mechanism of lightning initiation inside thunderstorms is one of the major unsolved mysteries in the atmospheric sciences (e.g., Rakov and Uman 2003, Rakov 2004, 2006). It has been the common view until recently that in order to initiate lightning at some location in a thundercloud, the electric field intensity at that location must reach a value large enough for conventional electrical breakdown to occur. In dry air at sea-level the breakdown field threshold, E_b , is about 2.6×10^6 V/m. However, decades of electric field measurements inside thunderstorms have failed to find electric field strengths close to the conventional breakdown threshold, even when the effects of precipitation and the lower pressure at cloud charge altitudes are taken into account. As an alternative to lightning initiation by conventional breakdown, various forms of runaway breakdown (breakdown caused by runaway electrons – see later discussion) have been proposed. All of these can potentially occur at a lower electric field level than does conventional breakdown.

A mystery perhaps related to the lightning initiation question is the mechanism of terrestrial gamma-ray flashes (TGF). TGFs are very intense bursts of high energy (up to 20 MeV) gamma-rays seen from space by satellites (Fishman et al. 1994, Smith et al. 2005). Recent results show that these bursts of gamma-rays originate from deep within the atmosphere, apparently from within thunderstorms (Dwyer and Smith 2005). This implies that the flux of high-energy radiation at aircraft altitude can at times be very large. Indeed, it is possible that during brief bursts, this high-energy radiation, originating from an area of 100 m dimension, may be larger than all other natural and man-made radiation over the entire surface of the planet combined (Dwyer 2007)! Dwyer et al. (2008) have shown that the gamma-rays in TGFs can be so intense that they launch beams of secondary electrons into the inner magnetosphere, the effects of which are seen thousands of kilometers away by spacecraft.

Recent observations have demonstrated that runaway electrons and their accompanying X-rays are produced, sometimes copiously, (1) within thunderstorm clouds, (2) by the stepped leaders of natural cloud-to-ground lightning, (3) by the dart leader of rocket-triggered lightning, and (4) by atmospheric-pressure laboratory sparks with voltages between about 500 kV and 1.5 MV. Runaway electrons occur when the electric force acting on fast electrons exceeds the effective drag force experienced by those electrons as they move through air (e.g., Wilson 1925, Gurevich 1961; Gurevich et al. 1992, Dwyer 2004). In such cases, an avalanche of relativistic electrons can develop that produces large quantities of X-rays and gamma-radiation through bremsstrahlung interactions with air. Considerable progress has been made in the last few years in understanding the production of runaway electrons in our atmosphere. Recent theoretical work by the FIT group (Dwyer 2003, 2007) has introduced a new mechanism for the electrical breakdown of air involving runaway electron production and positron and X-ray feedback.

A further important and possibly related question is how lightning propagates. It is known that in order to travel great distances through air, lightning forms a hot conductive channel called a leader. The leader provides a conductive path for the transport of electrical charge, allowing the lightning to propagate out of the thundercloud into regions with low ambient electric fields. For most lightning, this is accomplished by the negative stepped leader, which propagates in a series of discrete steps, roughly 50 m in length. Exactly how and why lightning moves in steps remains a mystery. However, because the lightning stepping process determines where lightning travels and ultimately what it strikes, understanding that process is crucial for lightning protection and safety. It was recently discovered by FIT and UF researchers at the ICLRT that large bursts of x-rays are associated with the formation of a lightning leader step. In other words, the production of runaway electrons and their accompanying x-rays are tied to how lightning propagates. These x-ray measurements also provide a powerful new tool for measuring properties of the stepped leaders that was not possible before. Because with each step, the leader must break down the air a large distance in front of the old leader channel, in some ways the questions about lightning stepping and lightning initiation may be related, especially in light of the potential role of runaway electrons in both processes. With the new instrumentation available at the ICLRT, we are in a position to greatly enhance our understanding in the underlying physics of lightning initiation and propagation.

While the lightning initiation processes in the thundercloud are relatively inaccessible to close measurement, lightning that is initiated near ground level and propagates upward into the thundercloud charge, thereafter initiating an electrical discharge closely resembling the latter portion of natural downward lightning, can be studied at close range using the rocket-and-wire triggering system presently in operation at the UF-FIT research facility (the ICLRT, International Center for Lightning Research and Testing). A review of the understanding of the artificial initiation of lightning by ground-based activity circa 2003 is given by Rakov and Uman (2003). Biagi et al. (2009) have added to this information and pointed the way to future research.

IV. Proposed Future Research

We propose now the skeleton of an ideal five-year future program to answer the four major unanswered questions in the lightning and thunderstorm electricity area. Overall, we envision a 5 year program with a total cost about \$20 M. The new UF/FIT equipment that is needed costs near \$6M and should be purchased early in the program. Subcontracts to others outside UF/FIT have a price-tag near \$2M. UF/FIT salaries, expense, and overhead is near \$2.5 M per year or \$12.5M for the five years.

The four major questions formulated below are each followed by (A) the experimental tools proposed to be added to the existing equipment used in the research reported in Sections I and II of this report, and (B) the expected results of the analysis of the newly-acquired experimental data and of theoretical studies:

1. How is lightning initiated inside thunderclouds? Are high energy radiation processes (X-rays, gamma rays, runaway electrons, cosmic rays) involved and, if so, how? By what process do thunderclouds produce terrestrial gamma-ray flashes (TGF's) (intense bursts of high-energy radiation seen from space and once on the ground at Camp Blanding)? Are these TGF's related to the lightning initiation process? What is the physics of "compact intracloud discharges" (short duration, isolated in-cloud lightning discharges that are apparently the most powerful natural radio emitters on Earth). Do they emit high energy radiation (gamma-ray bursts perhaps)? Are they related to the initiation process?

A. Experimental tools

- (a) Multiple-station (>10) ground-based x-ray (gamma ray) and multiple-station (>24) cosmic-ray-muon detection network (TERA) presently in place. Upgrade TERA with LaBr₃ detectors to replace NaI detectors (\$400K) and other minor upgrades.
- (b) Multiple-station ground-based cosmic-ray-induced rf pulse detection network (to be newly constructed, \$75K)
- (c) Ground-based electric field measuring network (dc – 20 MHz) at Camp Blanding and similar detection system in Gainesville, 45 km distant, and at the DuPont site 2-3 km from Camp Blanding. DuPont will be new. Most of the rest is in place.
- (d) X-ray camera (to be newly constructed \$500 K to \$1 M depending on the type of detection elements of which there will be 114)
- (e) Simultaneous in-cloud aircraft x-ray and electric field measurements (subcontracted, NASA ER-2, \$300 K per summer, including instrument integration, operations, ground support, and personnel involved)

- (f) Simultaneous x-ray (gamma ray) measurements on ground and on satellites (new component)
- (g) VHF lightning-breakdown mapping array: NASA NMIMT LMA (\$500 K for purchase, installation, and first summer operation, or subcontracted)
- (h) University of Alabama at Huntsville Dual-Polarization Doppler Radar (subcontracted, \$200 K per summer including first pass data analysis)
- (i) Ground-based electric field mill and field change array for cloud fields (dc to 100 Hz) (to be expanded from present or subcontracted at \$200 K initial cost plus \$50 K per summer)
- (i) Balloon measurements of electric fields and energetic electrons/positions (subcontracted, \$200 K per summer)
- (k) New VLF and dc-20 MHz electric field stations in the Caribbean for correlation with TGF's measured on satellites (\$200 K plus operating expenses)
- (l) New digitization, transmission, internet access, and storage techniques to be implemented for all data (\$2 M, breakdown to lengthy to include here)

B. Theory and Data Analysis

- (a) Cloud electric fields determined from measurement of rf pulses associated with cosmic ray showers
- (b) Mechanism for gamma ray production in thunderstorm
- (c) The mechanisms of lightning initiation as inferred from aircraft, balloon, and satellite measurements coordinated and simultaneous with ground-based measurements
- (d) Mechanisms and parameters of compact intracloud discharges
- (e) Improved simulations of air shower/runaway electrons/ rf emission
- (f) Realistic 3-D thunderstorm models incorporating runaway breakdown
- (g) A self-consistent runaway breakdown model
- (h) Improved Monte-Carlo code for treating thermal runaway and relativistic runaway electrons
- (i) The origin of TGF's

2. What are the mechanisms by which lightning propagates through many kilometers of air from the cloud to the ground? Are the observed X-rays associated with propagating leaders (and the runaway electrons that generate the x-rays) an important part of the propagation process? Can they be used as a process diagnostic? Once near the ground, how does lightning decide which object to strike? That is, what is the detailed physics of the attachment process to ground? Why does a large X-ray burst occur just before the return stroke? Does that mark the beginning of the return stroke or the beginning of the attachment process?

A. Experimental tools

- (a) High speed photographic equipment
 - i. 0.3 μ s resolution Model 570 Cordin high-speed camera (to be purchased, \$700 K)
 - ii. 3 μ s – 10 μ s resolution Phantom with accessories (3 additional units to be purchased at \$200 K per unit or \$600 K total)
 - iii. 10 ns resolution 8 channel telescopic photometer array (presently under construction by Dr. Moore)
- (b) Multiple-station (>10) ground-based x-ray (gamma ray) detection network. Upgrade by replacing NaI with LaBr₃ Detection (\$400 K)
- (c) Ground-based electric field measuring network (dc – 20 MHz) at Camp Blanding and similar detection system in Gainesville, 45 km distant, and at the DuPont site 2-3 Km from Camp Blanding (to be expanded to include the DuPont site)
- (d) VHF lightning-breakdown mapping array: NASA NMIMT LMA (subcontracted or \$500 K for first summer operation)
- (e) University of Alabama at Huntsville Dual-Polarization Doppler Radar (subcontracted for \$200 K per summer)
- (f) Ground-based electric field mill and field change array for cloud fields (dc to 100 Hz) (to be expanded from present or subcontracted at \$200 K initial cost plus \$50 K per summer)
- (g) X-ray camera (to be newly constructed \$500 K to \$1 M depending on the type of detection elements of which there will be 114)
- (h) Florida State fire tower moved and outfitted for elevated high-speed video observations (\$50 K)
- (i) New digitization, transmission, internet access, and storage techniques to be implemented for all data (\$ 2 M, breakdown to lengthy to include here)

B. Theory and Data Analysis

- (a) Correlated optical and x-ray locations of lightning leader-step formation

- (b) Mechanism of the attachment process from correlated sub-microsecond optical, dE/dt , and x-ray measurements
 - (c) Mechanism of x-ray production in leader steps
 - (d) Close (Camp Blanding) and distant (Gainesville, DuPont) simultaneously measured electric field waveforms and associated modeling to understand aspects of the attachment process
 - (e) Measured return stroke velocity and light profiles vs. height and their relation to channel currents and radiated electric and magnetic fields
3. What is the detailed physics of rocket-and-wire triggering of lightning and of upward lightning from tall structures in general? What can triggered lightning tell us about the initiation, propagation, and ground attachment of natural downward lightning?
- A. Experimental tools
- (a) High speed photographic equipment
 - i. 0.3 μ s resolution model 750 Cordin high-speed camera (to be purchased, \$700 K)
 - i.i. 3 μ s – 10 μ s resolution Phantom with accessories (3 additional units to be purchased at \$200 K/unit or \$600 K total)
 - iii. 10 ns resolution 8 channel telescopic photometer array (presently under construction by Dr. Moore)
 - (b) Ground-based electric field measuring network (dc – 20 MHz) at Camp Blanding and similar detection system in Gainesville, 45 km distant and at the DuPont site 2-3 km from Camp Blanding (to be expanded to include the DuPont site)
 - (c) X-ray camera (to be newly constructed \$500 K to \$1 M depending on the type of detection elements of which there will be 114)
 - (d) Multiple-station (>10) ground-based x-ray (gamma ray) detection network. Upgrade by replacing NaI with LaBr₃ Detection (\$400 K)
 - (e) Ground-based electric field mill and field change array for cloud fields (dc to 100 Hz) (to be expanded from present or subcontracted at \$200 K initial cost plus \$50 K per summer)
 - (f) Triggered-lightning current measurements (0.1 A to 60 kA) (in place except for new data acquisition and storage, see "k" below)
 - (g) VHF lightning-breakdown mapping array: NASA NMIMT LMA (subcontracted or \$500 K for first summer)

- (h) University of Alabama at Huntsville Dual-Polarization Doppler Radar (subcontracted for \$200 K per summer)
- (i) High speed optical spectrometer (Subcontract from University of Alabama at Huntsville, \$100 K)
- (j) Florida State fire tower for elevated optical observations (\$50K)
- (k) New digitization, transmission, internet access, and storage techniques to be implemented for all data (\$ 2M, breakdown too lengthy to include here)
- (l) New launch control facility (\$75 K)

B. Theory and Data Analysis

- (a) On conditions necessary to trigger lightning in Florida
- (b) Characteristics of precursor pulses and sustained leaders in 50 triggered lightning events
- (c) Location and magnitude of the cloud charges associated with triggered lightning
- (d) Location of cloud-to-ground and in-cloud lightning channels from optical, VHF/UHF, and x-ray measurements
- (e) Atmospheric charge distribution near ground, the shielding layer, horizontal and vertical extent
- (f) Differences in triggering with positive vs. negative charge overhead
- (g) Polarization of cloud ice particles and the probability of triggering
- (h) Electric field vs. height in the ambient atmosphere prior to triggering lightning
- (i) Characterization of natural upward lightning discharges initiated from tall TV towers (as determined from optical and electromagnetic observations at the Gainesville station)
- (j) Long distance ELF/VLF propagation studies of triggered lightning at Camp Blanding, observed at McMurdo Station, Antarctica

4. What are the significant effects of in-cloud and cloud-to-ground lightning on the regions of the atmosphere (a) between thundercloud tops and the ionosphere and (b) in the ionosphere and magnetosphere? Such effects include energetic ($> \sim 50$ keV) electron precipitation from the Earth's radiation belts, sprites, sprite halos, elves, blue jets and gigantic jets. What can long-distance ELF/VLF observations of lightning tell us about the lightning energy that couples to these regions of near-Earth space? How is the initiation of these events related to the detailed properties of the causative lightning flash? Can rocket-and-wire triggered lightning be used to better understand these effects?

A. Experimental tools

- (a) Ground-based electric field measuring network (dc – 20 MHz) at Camp Blanding and similar detection system in Gainesville, 45 km distant and 2-3 km away at DuPont (to be expanded for DuPont)
- (b) Triggered-lightning current measurements (0.1 A to 60 kA) (in place except for new data acquisition and storage)
- (c) Continuous wideband array of 5 electric field systems throughout Florida and Georgia (\$100 K)
- (d) High speed photographic equipment
 - i. 0.3 μ s resolution Model 570 Cordin high-speed camera (to be purchased, \$700 K)
 - i.i. 3 μ s – 10 μ s resolution Phantom with accessories (3 additional units to be purchased at \$200 K/unit or \$600 K total)
 - iii. 10 ns resolution 8 channel telescopic photometer array (presently under construction by Dr. Moore)
- (e) Additions to ionospheric high-speed photometer arrays (under construction by Dr. Moore) for multiple wavelengths, mobile operations, and new lenses (\$280 K)
- (f) Demeter satellite measurements of electron-precipitation and ELF/VLF radiation from natural and triggered-lightning
- (g) New digitization, transmission, internet access, and storage techniques to be implemented for all data (\$2 M, breakdown to lengthy to include here)
- (h) Long-distance ELF/VLF observations in Alaska and McMurdo Station, Antarctica
- (i) Intermediate-distance ELF/VLF observations throughout the Southeastern US (\$100 K for ELF/VLF receivers)

B. Theory and Data Analysis

- (a) Observed propagation of triggered-lightning signals to McMurdo Station, Antarctica
- (b) Measured properties of elves from correlated triggered and natural lightning measurements at close range
- (c) Is there a relation between transient luminous events above thunder cloud tops and compact intracloud discharges?
- (d) The relationship between long-distance and intermediate-distance ELF/VLF observations of rocket-triggered lightning electromagnetic radiation

- (e) Observed sub-microsecond properties of elves from correlated triggered and natural lightning measurements at close range
- (f) Ionospheric disturbances produced by natural and rocket-triggered lightning
- (g) Properties of sprites, halos, and elves produced by natural and rocket-triggered lightning
- (h) Energetic electron precipitation from the Earth's radiation belts. How are radiation belt dynamics affected by lightning electromagnetic radiation?
- (i) Experimental determination of the coupling of lightning energy to the Earth's Ionosphere and Magnetosphere
- (j) Positive polarity triggered lightning ICC and its relation to sprite and sprite halo initiation
- (k) Relation of return stroke current and speed to elves production, lightning-induced electron precipitation, and Earth-ionosphere waveguide excitation

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